

On Modeling Air/Spaceborne Radar Returns in the Melting Layer

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Abstract—The bright band is the enhanced radar echo associated with the melting of hydrometeors in stratiform rain. To simulate this radar signature, a scattering model of melting snow is proposed in which the fractional water content is prescribed as a function of the radius of a spherical mixed-phase particle consisting of air, ice, and water. The model is based on the observation that melting starts at the surface of the particle and then gradually develops toward the center. To compute the scattering parameters of a nonuniform melting particle, the particle is modeled as a sphere represented by a collection of 64^3 cubic cells of identical size where the probability of water at any cell is prescribed as a function of the radius. The internal field of the particle, used for deriving the effective dielectric constant, is computed by the conjugate gradient and fast Fourier transform (CGFFT) numerical methods. To make computations of the scattering parameters more efficient, a multilayer stratified-sphere scattering model is introduced after demonstrating that the scattering parameters of the nonuniformly melting particle can be accurately reproduced by the stratified sphere. In conjunction with a melting layer model that describes the melting fractions and fall velocities of hydrometeors as a function of the distance from the 0°C isotherm, the stratified-sphere model is used to simulate the radar bright-band profiles. These simulated profiles are shown to compare well with measurements from the Precipitation Radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite and a dual-wavelength airborne radar. The results suggest that the proposed model of a melting snow particle may be useful in studying the characteristics of the bright-band in particular and mixed-phase hydrometeors in general.

Index Terms—Air/spaceborne radar, effective dielectric constant, electric scattering, melting layer, radar bright band.

I. INTRODUCTION

THE bright band, a layer of enhanced radar reflectivity associated with melting snow, is often observed in stratiform rain. The primary cause of the enhancement is a rapid increase in the dielectric constant of hydrometeors at the top of the melting layer. After reaching a maximum, the reflectivity decreases because of an increase in particle velocities and a decrease in the effective particle size. Understanding the microphysical properties of melting hydrometeors and their electric scattering and propagation effects is crucial in estimating parameters of the precipitation from spaceborne radar and microwave radiometers [1]–[4], such as the Precipitation Radar (PR) and the Microwave Imager (TMI) aboard the Tropical Rain Measuring Mission (TRMM) satellite. Simulations of radar profiles of the bright band generally require two models: a meteorological melting layer model that describes the complex physical phenomena that couples the particle melting with the dynam-

ical and thermodynamical processes within the melting layer; a particle scattering model of melting snow that characterizes the scattering and propagation properties of hydrometeors at microwave and millimeter wavelengths. While both models are important, our focus in this study is on the analysis of the particle scattering model. This involves specifying the distribution of water within the particle and a method for computing its scattering and absorption properties.

Accurate estimates of the effective dielectric constants of melting hydrometeors at microwave frequencies are essential to calculate the radar reflectivity factor and path attenuation. Because of the complex nature of the melting process and lack of experimental data on the effective dielectric constant of the melting snow, computations of the scattering properties of melting hydrometeors rely on particle melting models. Two types of model often appear in the literature: one is the uniformly mixed model where the water fraction is constant (uniform mixture) throughout the particle; another is the two-layer concentric-sphere model where the water is confined to the outer shell and snow to the inner core. The most commonly used formulas for the effective dielectric constant for uniformly melting snow are those of Maxwell Garnett [5] and Bruggeman [6]. However it is physically unclear as to which formula should be used, and in the case of Maxwell Garnett formulation, which component should be selected as matrix or inclusion in the mixture. The formulas, moreover, can not be used to distinguish between uniform and nonuniform mixing of the constituents.

Meneghini and Liao [7] have proposed an expression for the effective dielectric constant ϵ_{eff} for ice/snow–water mixtures for wavelengths between 3 and 28 mm in terms of the fractional water volume and wavelength, based on a parameterization of the numerical results obtained from realizations of mixed-phase hydrometeors composed of air, ice, and water. The results are derived under the assumption that the air, ice, and water are uniformly mixed. However, observations [8], [9] indicate that the melting of snow aggregates and graupel starts at the surface of the particle and progresses toward the center. It is therefore reasonable to model the melting particle as a nonuniform mixture with a water fraction that decreases toward the center. In this paper, we focus on the discussion of effective dielectric constant of melting hydrometeors by constructing a nonuniformly melting model of snow, followed by a simulation of the radar bright band and comparisons to air- and spaceborne radar measurements.

Section II of the paper gives a derivation of ϵ_{eff} and a discussion on its range of validity. Computations of ϵ_{eff} are made in Section III for dry and melting snow where the fractional ice and water contents are prescribed as a function of radius of the air–ice and snow–water spheres. In Section IV a multilayer

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stratified-sphere model is constructed with scattering characteristics similar to those obtained from the conjugate gradient and fast Fourier transform (CGFFT) scattering model. Simulations of the radar bright-band profiles for the cases of TRMM PR and a dual-wavelength airborne radar are made in Section V using a stratified-sphere model in which the effective dielectric constant for a uniform mixture is used at each layer. A summary of the study is given in Section VI.

II. THEORETICAL BACKGROUND OF ε_{eff}

Let $\mathbf{E}(\mathbf{r}, \lambda)$ and $\mathbf{D}(\mathbf{r}, \lambda)$ be the local electric and dielectric displacement fields at free-space wavelength λ , satisfying

$$\mathbf{D}(\mathbf{r}, \lambda) = \varepsilon(\mathbf{r}, \lambda)\mathbf{E}(\mathbf{r}, \lambda). \quad (1)$$

In view of the local constitutive law described by the above equation, the bulk effective dielectric constant is defined as the ratio of the volume averages of \mathbf{D} and \mathbf{E} fields of a composite material [10]. This relationship can be written as

$$\varepsilon_{\text{eff}} \iiint_V \mathbf{E}(\mathbf{r}, \lambda) dv = \iiint_V \mathbf{D}(\mathbf{r}, \lambda) dv \quad (2)$$

where V is the entire volume of the particle. If the particle, composed of two materials with dielectric constants ε_1 and ε_2 , is approximated by N equivolume elements, the ε_{eff} can be written

$$\varepsilon_{\text{eff}} = \frac{\left(\varepsilon_1 \sum_{j \in M_1} E_j + \varepsilon_2 \sum_{j \in M_2} E_j \right)}{\left(\sum_{j \in M_1} E_j + \sum_{j \in M_2} E_j \right)}. \quad (3)$$

The notation $\sum_{j \in M_1}$ and $\sum_{j \in M_2}$ denotes a summation over all volume elements comprising materials 1 and 2, respectively. Dividing both numerator and denominator by N in (3), and letting f_1 and f_2 be the fractional volumes of component 1 and 2, respectively, ε_{eff} becomes

$$\varepsilon_{\text{eff}} = \frac{(\varepsilon_1 f_1 \langle E_1 \rangle + \varepsilon_2 f_2 \langle E_2 \rangle)}{(f_1 \langle E_1 \rangle + f_2 \langle E_2 \rangle)} \quad (4)$$

where $f_1 + f_2 = 1$, and $\langle E_1 \rangle$, $\langle E_2 \rangle$ represent the mean fields in materials 1 and 2. In our study, the internal fields appearing on the right-hand sides of (3) and (4) are computed by the CGFFT numerical procedure in which the volume enclosing the total particle is divided into $64 \times 64 \times 64$ identical cells. In computing ε_{eff} , only that component of the internal field aligned with the incident E field direction is used so that if the incident field is polarized in \hat{x} direction, $\langle E_1 \rangle$ and $\langle E_2 \rangle$ represent the x component of the internal fields averaged over the volumes of materials 1 and 2.

VI. SUMMARY

The internal electric field of mixed-phase particles can be used to calculate an effective dielectric constant ε_{eff} . In this paper, we have done this by using the conjugate gradient and fast Fourier transform techniques to solve for the internal field. Previous work along these lines [7], [14] focused on computations of ε_{eff} for uniform mixtures where the probability of ice, air, or water is independent of location within the particle. As shown in the first part of the paper, an effective dielectric constant also can be computed for cases where the fractional water or ice content varies with radius. In the case of an ice-air mixture, it was found that radial gradients in the fractional ice content have only a negligible effect on ε_{eff} and that the scattering properties of the dry snow mixture depend almost exclusively on particle mass. On the other hand, for a snow-water sphere, the radial gradient in the fractional water content has a strong influence on the particle scattering properties. The CGFFT method can be used to compute ε_{eff} for radial gradients in the snow-water mixture. However, the computational requirements are formidable. To simplify the problem, it has been shown that the particle model can be replaced by a stratified sphere where the ε_{eff} at the i th layer is obtained from CGFFT-derived value of ε_{eff} for a uniform mixture with the same fractional water/snow content of that layer.

As an application of the result, the stratified sphere model for nonuniform melting snow was used to generate radar bright-band profiles which were compared with data from the TRMM PR at 13.8 GHz and from a dual-wavelength airborne radar at 10 and 35 GHz. For the TRMM PR, the Marshall-Palmer raindrop size distribution was used as input to the melting layer model. For the dual-wavelength case, an iterative procedure was applied to the data to determine the parameters of the size distribution in rain which were then used to generate the bright-band profiles at both frequencies. The results show that the simulated bright-band profiles are in good agreement with the measurements and suggest that the proposed particle scattering model yield reasonable agreement with both single and dual-wavelength radar measurements.

As with nearly all radar simulations of the melting layer, there are a number of free parameters that must be assumed in the calculations. These include snow density, effects of drop aggregation and break-up, and various assumptions included in the particle melting model. In our case, the quantity β , which determines that radial gradient of water within the melting particles, is an additional free parameter whose value was chosen to yield the best agreement with the radar measurements. High-resolution images of melting particles and theoretical work that yield details on the distribution of melt water within the particle will be needed to determine this parameter independently. Another deficiency in the particle model is its restriction to spheres. While nonspherical particles are essential for understanding cross-polarization effects, for copolarized measurements of the radar reflectivity at near-nadir incidence, particle shape is a second-order effect. Nevertheless, an extension of the theory to nonspherical mixed-phase particles would be useful not only in radar polarimetric applications but in microwave radiometry as well.